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Interpretation of Multiwavelength Observations of Nonthermal Extragalactic Radio Sources

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Abstract

Radio observations of compact extragalactic radio sources study the emission at parsec scales, and are generally interpreted in terms of a relativistic jet model. The "inner jet" region that connects the parsec-scale jet with the central engine can only be observed at wavelengths shorter than those in the radio regime, namely the submillimeter to γ-ray portions of the spectrum. Multiwavelength observations demonstrate that there is a strong relationship between the nonthermal emission at lower and higher frequencies. Future multiwavelength monitoring holds the key to understanding the geometry and physics of the inner jet.

1. Introduction

At the sub-milliarcsecond resolution of VLBI, we find that a majority of strong, compact, extragalactic radio sources have core-jet structure [PeR88]. The almost universally adopted interpretation is that the emission arises from well-collimated jets of nonthermal plasma flowing out from the nucleus at relativistic speeds (see [Mar93] for a recent review of this model and the observations that support it). The "core" is a very compact, stationary component at one end of the jet. Nevertheless, its size is 2–3 orders of magnitude larger than the dimension of the central engine according to the favored accreting black hole paradigm. High-frequency VLBI is crucial for exploring the properties of the core and comparing these with the expectations of the jet model. Still, it is likely that the connection between the radio jet and the central engine can be studied fully only by observing at frequencies much higher than is possible with VLBI.

In general, one expects high-frequency emission to arise mainly from the region closest to the ultimate energy source, since electrons that radiate at these frequencies lose

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energy rapidly once they exit the site of energy injection. Nevertheless, rejuvenation of these electrons can occur far downstream, for example in shock waves. In addition, inverse Compton scattering can produce X-rays and γ-rays wherever high-energy electrons and a strong photon field are found. It is therefore important to find ways to determine where the high-frequency emission arises so that the details of the observed time variations, spectra, etc., can be related to the physics and geometry of the source. Since sub-milliarcsecond resolution is not currently possible at wavelengths shorter than 1.3 mm, we must rely on comparison of multiwavelength observations with theoretical models to establish where the emission arises and how this relates to the physics and structure of the jet.

2. A Quick Review of Multiwavelength Observations

Multiwavelength spectra of compact extragalacitc sources exhibit flat radio spectra (known to be caused mainly by the superposition of self-absorbed components in the jet), which turn over and become optically thin at frequencies above a few 10^{10} to $\sim 10^{12}$ Hz. Above the turnover frequency, [Lan86] find that the spectra become monotically steeper with frequency, although the spectra measured by [Bro89] are in many cases well described by power laws over several decades of frequency.

BL Lac objects tend to be highly variable at X-ray energies and to have steeper X-ray spectra than do quasars [Mri92]. The spectra of some BL Lac objects appear to be continuous from radio to X-ray frequencies, indicating a common emission mechanism — presumably synchrotron radiation — in the compact jet. Quasars are also variable at X-ray energies, although not many cases are well documented. The X-ray spectra of quasars are rather flat [WiE87], too much so to be explained as continuations of the optical-uv emission. The recent detections of a number of quasars and BL Lac objects containing compact jets by the *Compton Observatory* at hard γ-ray energies demonstrate that a significant, in some cases dominant, fraction of the nonthermal luminosity is emitted at extremely high energies ([Har92]; [DeS92]). The γ-ray flux from the quasar 3C 279 was reported to be variable by a factor of three over a 4-month period and also to be significantly variable on a timescale of a few days [Kan92].

There are a number of studies that have demonstrated that flares in nonthermal sources are often broadband in nature. For example, a direct correspondence between X-ray and radio–infrared variability has been found in 3C 279 [Mak89]. In the case of BL Lac, [Kaw91] found that the X-ray flux was correlated with the submillimeter-wave flux. [Bre90] and [HuB92] find that, in BL Lac and several other blazars, there is no significant time delay between features in the optical and infrared light curves, but that there is a delay of about 1 year between the weakly correlated optical and radio variations. The optical variations can be characterized by a combination of shot noise and flicker, whereas the radio variations have power spectra similar to shot noise. The conclusion is that flickering is a high-frequency phenomenon in the sources studied, and that the radio emitting region is larger than, but connected to, the site of the optical emission.

3. A Quick Review of Models for the Inner Jet

Two possible models linking the parsec-scale jets with the central engine are tapered, accelerating jets and highly relativistic particle beams (see Fig. 1). For the beam model, [Phi87] and [MeK89] have shown that up-scattering of the uv photons emitted by the accretion disk decelerates the electron-positron stream to a terminal bulk Lorentz factor ~ 10. The scattering, along with plasma instabilities, can also randomize the pitch angles such that the beam becomes a flowing plasma by this point, which corresponds to the core of the radio jet. A model intermediate between these two describes the inner jet as a beam of relativistic plasma flowing along essentially straight field lines [Bak88]. At some distance from the central engine, plasma instabilities introduce a substantial random component to the magnetic field such that the source emits incoherent synchrotron radiation downstream of this point.

If the acceleration of the relativistic electrons occurs only in the region closest to the central engine, the synchrotron emission at uv, optical, and IR frequencies is confined to this region as well, which is opaque to radio emission ([Mar80]; [MGC92]). The dependence of the magnetic field, relativistic electron density and maximum energy, and bulk Lorentz factor on distance down the jet leads to a frequency-dependent size of the emission region and a steep spectral index. The timescale of variability is therefore shorter at higher frequencies and time delays are expected as a flare propagates from high to low frequencies. Outside of the UVOIR region, the highest energy electrons emit only at lower frequencies, having suffered from radiative and adiabatic losses. However, if the inner jet does not open too abruptly, the maximum radio emission occurs where the Lorentz factor, and hence the Doppler boosting, is strongest. This region is then identified as the radio core, with the radio jet visible on the downstream side. Substantial self-Compton γ-ray and X-ray emission can occur either in the UVOIR region or the radio core (see [MGC92]). In addition, (inverse) Compton relection of optical and uv photons from the accretion disk can take place in the UVOIR region, producing X-rays and γ rays [DSM92].

Compton reflection of the optical and uv photons from the accretion disk (or ambient photons from emission-line clouds or regions of electron scattering) off a highly relativistic stream of electrons [MeK89] emits γ rays from the deepest part of the inner jet and X-rays somewhat downstream of this, with the nonthermal optical to radio emission occurring farther out.

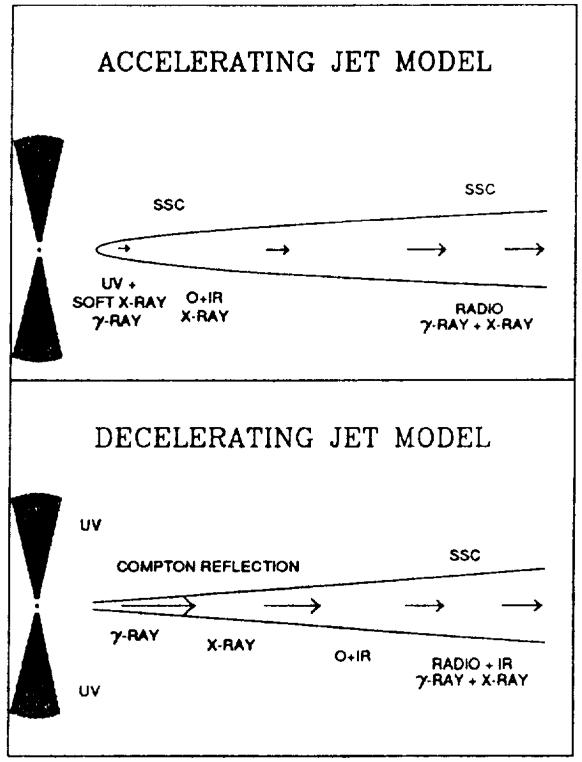

Figure 1. *Two basic models (not drawn to scale) for the inner jet that connects the compact radio jet with the central engine, here depicted as a massive black hole with an accretion disk. The lengths of the arrows inside each jet correspond to the magnitude of the bulk Lorentz factor of the jet flow on a logarithmic scale. The primary emission mechanism of each region is indicated above the jet, with "SSC" corresponding to synchrotron self-Compton emission. The main frequency bands of the nonthermal emission are indicated below the jet, with synchrotron or Compton reflection on top and self-Compton on bottom.*

4. Tests of the Models through Multiwavelength Observations

There are three aspects of multiwavelength observations that can be used to test models for the emission mechanisms and source structure and physics: the value of the spectral index, the relative flux densities at different wavebands if the spectra do not connect smoothly, and correlated (or uncorrelated) variability of brightness.

The spectral index of a given uniform synchrotron-emitting source reflects the energy distribution of the relativistic electrons. Any spectral steepening corresponds to radiative losses competing with energy gains. In the accelerating jet model, however, the source is nonuniform, with gradients in magnetic field, etc. The value of the spectral slope therefore results from a combination of the electron energy distribution and the gradients of the physical quantities, which in turn depends on the geometry of the jet (see [Mar80] and [GMT85] for the relevant relations).

While it appears well established that the nonthermal radio to optical emission is synchrotron radiation, it is not so clear what causes the X-ray and γ-ray emission. For quasars and some BL Lac objects, the flat (spectral index $\lesssim 1.0$) X-ray spectra suggest that inverse Compton emission might be the main mechanism. If this is self-Compton scattering, the ratio of γ-ray to X-ray luminosity cannot exceed that of X-ray to infrared luminosity (see [MaB92] and [BlM92]). In addition, the value of the spectral index across one waveband is directly related to that of another, although not as trivially as usually asserted.

In each of the models for the inner jet, the emission regions at different wavebands are connected but lie at different distances from the central engine. One can therefore potentially use multifrequency observations to discriminate among the models. Disturbances propagating down the jet are time-delayed at different wavebands, depending on the location of the primary emission region at each frequency. Measurement of such time delays would therefore reveal the jet geometry, the location of the particle acceleration, and possibly the speed of the flow as a function of distance along the jet.

Fluctuations in jet flow can also cause shocks to form. [BlK79] proposed that such shocks correspond to the apparently superluminal knots found in VLBI images of compact jets. [MaG85] showed that, at high frequencies, the emission behind the shock has frequency-dependent structure, with the highest frequency radiation confined to the region immediately behind the shock front where the emitting electrons have not yet suffered significant radiative energy losses. Such shocks can occur in any portion of the jet between the base and the region near the radio core. (Radiative losses are probably not important far downstream of the core.) [MGT92] have explored the variations in brightness and spectrum expected from a shock propagating down a jet containing hydromagnetically turbulent plasma. The overall evolution of the flare spectrum is a rather abrupt rise, followed by a decrease in turnover frequency as the peak flux remains roughly constant, and eventually a decline. As the shock encounters turbulent eddies, simultaneous brightness and polarization fluctuations occur at higher frequencies with slightly time-delayed and less pronounced variations at lower frequencies (but still above the self-absorption turnover).

5. Conclusions

The region between the radio core and the central engine is the great unexplored region of compact jets, yet that is where the most interesting physics is likely to occur. As millimeter and (let's hope!) submillimeter wave VLBI progresses over the next several years, we may eventually be able to image the core and perhaps part of the inner jet. During the same time period, the availability of the *Compton* Gamma Ray

Observatory, *ROSAT* and *ASTRO-D*, as well as ground-based radio, submillimeter, infrared, and optical observatories provides an outstanding opportunity to undertake coordinated multiwavelength observations. Such campaigns, combined with theoretical models, promise to unlock the secrets of the inner jet.

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